Direct measurement of population-induced broadening of quantum well intersubband transitions

Yuanjian Xu,[a] Gilad Almogy, John O'Brien, Ali Shakouri, Weihua Xu, Randal A. Salvatore, and Amnon Yariv

Department of Applied Physics 128-95, California Institute of Technology, Pasadena, California 91125

The dependence of the absorption spectral linewidth of quantum well intersubband transitions on the electron population in the well is experimentally demonstrated. We show that the dependence of the spectral linewidth on the population is substantial and accounts for some of the broadening previously attributed to donor scattering. © *1997 American Institute of Physics.* [S0003-6951(97)04530-0]

In the single band model, also known as the parabolic effective mass model, intersubband transitions in quantum wells (QWs) are discrete. In practice, electron-electron interaction, QW width nonuniformity, electron interactions with rough interfaces and with impurities and their enhancement by electric fields, and the optical and acoustic phonons contribute to the experimentally observed linewidth of intersubband transition in QWs.[1–5] There have been quite a few theoretical reports to explain the experimental observation,[1–8] and, there has been controversy over the contribution of population density to the intersubband broadening. Bandara *et al.*[6,7] predicted that the dependence of the exchange interaction on the in-plane momentum ($\mathbf{k}_\parallel$) could contribute a substantial fraction of experimentally observed linewidths. Zaluzny,[8] on the other hand, claimed that the $\mathbf{k}_\parallel$ dependence is offset by the depolarization and excitonlike manybody effects. In this letter, we report on the experimental study of the dependence of intersubband transition broadening on electron population using a structure consisting of 50 periods of an asymmetric coupled double QWs (ACDQWs). External applied bias was used to shift the population between the coupled QWs whose absorption was measured with a monolithically integrated QW infrared photodetector (QWIP) directly on the ACDQW structure.[9,10]

The monolithically integrated structure was grown by molecular beam epitaxy on a (100) semi-insulating GaAs substrate. The ACDQWs consisted of an undoped 9-nm-thick GaAs narrow well, an undoped 3-nm-thick $Al_{0.4}Ga_{0.6}As$ barrier, and a selectively doped 10.8-nm-thick GaAs wide well. The wide well was nominally Si doped to 2×10^{18} cm^{-3} from 0.5 to 4.5 nm away from the barrier. The periods were separated by 42.2 nm of undoped $Al_{0.4}Ga_{0.6}As$ layers. This structure was designed to provide the largest possible charge transfer between the narrow well and the wide well with external applied bias. The absorption spectrum of the monolithically integrated QWIP was designed to overlap with that of the narrow well in the ACDQWs, while the wide well in the ACDQWs had an absorption spectrum peaked at the tail of the QWIP photoresponse spectrum. The QWIP was separated from the ACDQW structure by a 0.6-μm-n^+-GaAs and a 0.2-μm GaAs buffer layer. The QWIP consisted of 15 periods of 6.5-nm-thick Si-doped GaAs wells with nominal doping density of 1.1×10^{12} cm^{-2} and 44-nm-thick $Al_{0.18}Ga_{0.82}As$ barriers. The absorption spectrum of the grown structure, shown in Fig. 1, was performed using Fourier transform spectrometer with 1000 K blackbody radiation source. The sample was prepared in multiple pass geometry using 45° polished edge mirrors. The absorption spectrum of ACDQWs was measured by removing the QWIP layer. The QWIP absorption spectrum was calculated from the spectra of the ACDQWs with and without QWIP.

The monolithic integrated device, shown in the inset of Fig. 2, was mesa structure fabricated by two-step wet etching. The linewidth measurements for different external biases on the ACDQW structure were made at 10 K with constant bias on the QWIP. Figure 2 shows the absorbance spectrum calculated from the ratio of the photoresponse spectra of the QWIP while the ACDQWs were under different biases. By curve fitting the result, the integrated absorbance for the ACDQWs at different biases was obtained. As shown in Fig. 3(a), the integrated absorbance increases almost linearly with the application of external bias for the narrow well transition, corresponding to the transfer of population from the wide well to the narrow well. At zero bias, the population in the narrow well is about 0.5×10^{12} cm^{-2} and the broadening is $\Gamma \sim 3.75$ meV. As is clearly shown in Fig. 3(b), the broadening increases with external bias. From the integrated absorbance and the ACDQW parameters, the population in the narrow well was calculated. Before the
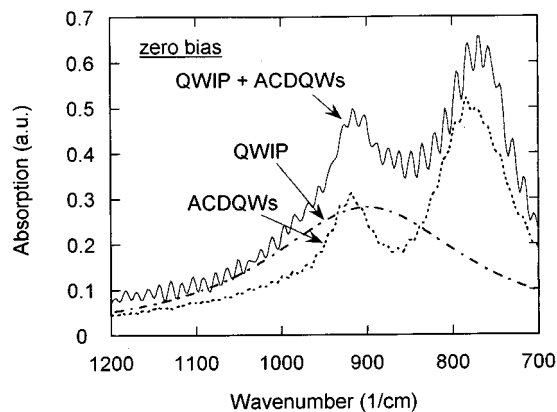

FIG. 1. Absorption spectra of the grown structure at room temperature.

[a]Electronic mail: xjxu@cco.caltech.edu

Report Documentation Page

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **AUG 1997**	2. REPORT TYPE	3. DATES COVERED **00-08-1997 to 00-08-1997**
4. TITLE AND SUBTITLE **Direct measurement of population-induced broadening of quantum well intersubband transitions**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **California Institute of Technology,Department of Applied Physics,Pasadena,CA,91125**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

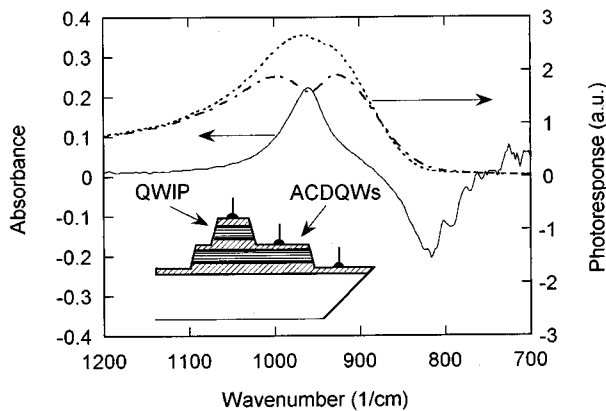| 16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES **3**	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**			

FIG. 2. Absorbance spectrum of the ACDQWs, calculated from the ratio of the photoresponse spectra of the QWIP. Inset: the monolithic integrated device structure.

FIG. 4. Experimental (a) integrated absorbance and (b) FWHM vs temperature for the narrow and wide wells.

conclusion of population-induced linewidth broadening being measured could be made, different broadening mechanisms are reviewed. The contribution from electron-electron dephasing broadening is expected to be small at these populations.[1] From the theoretical model,[4] and from the bias-induced broadening of constant population wells, the bias-induced broadening due to interface roughness and impurity scattering was estimated to contribute less than 1 meV to the measured full width at half-maximum (FWHM). The effective nonparabolicity created by the in-plane momentum dependence of the exchange interaction[9] can be one of the main factors which could explain the measured broadening. It should be noticed that the single-particle energy band non-parabolicity may also contribute to the linewidth[11] (at most up to ~4.5 meV at the highest bias), part of which will be compensated by depolarization and exciton effects. Because the exchange interaction makes a large contribution to the broadening, we expect that the depolarization and exciton effects may contribute by reducing the theoretical broadening,[8] but they will not change the situation drasti-
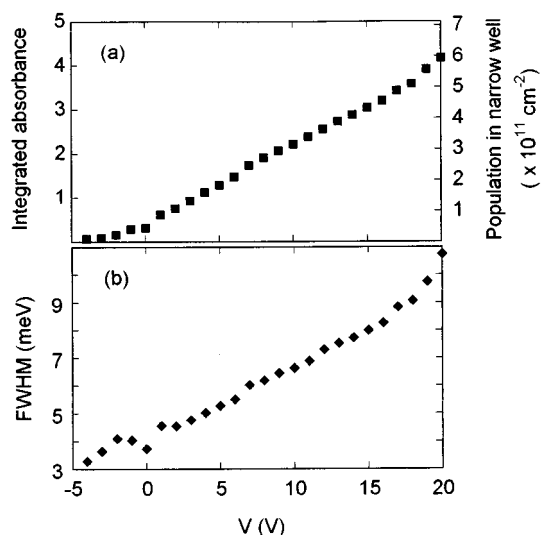

FIG. 3. Absorption characteristics of the narrow well as a function of external bias at $T = 10$ K. (a) The integrated absorbance and population in the narrow well vs external bias. (b) FWHM vs external bias.
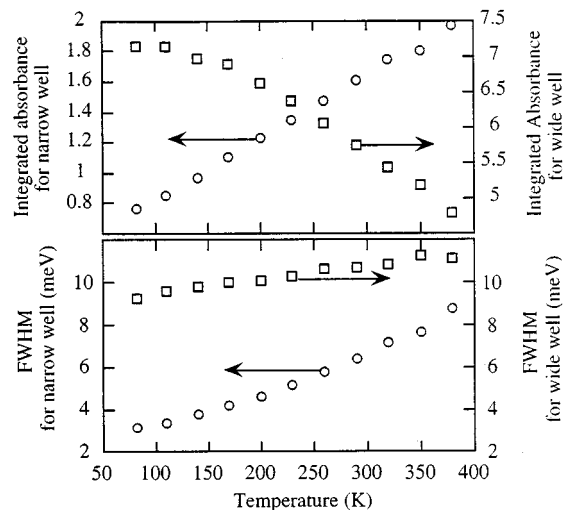
cally. Our experimental results show that the linewidth increases with the electron population instead of the predicted constant broadening.[8] For populations less than 1 $\times 10^{11}$ cm^{-2}, the minimum broadening is limited by other broadening mechanisms. When the population is around 4 $\times 10^{11}$ cm^{-2} the ground states anticross. The delocalization of the ground states between the two wells at the crossover biases of around 14 V is expected to lead an increase in impurity scattering and in field-induced scattering at the interfaces. Figure 3 shows that this broadening was not significant as no appreciable peak in the FWHM was measured for these biases. The expected crossing of the ground states at high biases was supported by the measurement of a redshift in the absorption peak position.

As a further check on our results, the absorption spectra at different temperatures were measured in multiple pass geometry using 45° polished edge mirrors. No bias was applied so that the population of the narrow QW was a function of temperature only. With the given doping density, the population changes in the narrow well and the wide well with temperature are due to electron redistribution between the coupled QWs and the bound state energy shifts caused by manybody effects. The integrated absorbance and the FWHM as a function of temperature for both the narrow and wide wells are plotted in Fig. 4. At room temperature, the population in the narrow well increased to about 22% of the total population, and the corresponding broadening was Γ ~6.6 meV. The lowest temperature for this multiple pass absorption experiment is limited to 83 K due to the experimental setup. It is seen in Fig. 4 that varying the temperature from 83 to 380 K caused an increase of the linewidth of 5.5 meV (from 3.2 to 8.7 meV) in the narrow well. At the same time, the FWHM of the wide well increased by only 1.9 meV, from 9.3 to 11.2 meV. Apparently, the linewidth due to temperature effect is significant. This could be explained through the occupation of higher momentum states at higher temperatures, and thus the increased effect of nonparabolicity due to single or many-particle effects. As the temperature increased from 83 to 380 K, the population-induced broadening in the wide well, whose population dropped, acted

counter temperature-induced increase in linewidth. In the narrow well, which gained population, the population-induced broadening assisted the linewidth increase due to the temperature effect. The large difference of the FWHM between low and room temperature (much larger than the typically measured value for constant well population) is again an indication of the important role of population-induced broadening in intersubband transitions.

Although the population dependence of intersubband transition linewidth may be material dependent, our experimental results show that population-induced broadening is very important in the spectral measurement of intersubband transitions in QWs. Even with the donors 0.5 nm away from the 3-nm-thick barrier in our experiment, a broadening as small as 3.75 meV was achieved. Thus, the broadening may not be significantly decreased by separating the donors from the wells when a large electron population is required. In view of our results and using a self-consistent solution, we reanalyzed a previous experiment where the broadening was measured as a function of donor separation from the well.[12] We deduce that the main cause for the reduction in linewidth observed in donor-well separation was the resultant reduction in the well's ground state population rather than the increased donor-electron separation itself.

In conclusion, we observed an increase of the intersub-band absorption linewidth with increasing electron density using field-induced charge transfer and thermally induced charge transfer. This increase is attributed mainly to the sub-band filling.

[1] P. Sotirelis, P. von Allmen, and K. Hess, Phys. Rev. B **47**, 12744 (1993).
[2] H. Sakaki, T. Noda, K. Hirakawa, M. Tanaka, and T. Matsusue, Appl. Phys. Lett. **51**, 1934 (1987).
[3] W. T. Massel, Phys. Rev. Lett. **66**, 1513 (1991).
[4] R. Ferreira and G. Bastard, Phys. Rev. B **40**, 1074 (1989).
[5] P. J. Price, Ann. Phys. (N.Y.) **133**, 217 (1981).
[6] K. M. S. V. Bandara, D. D. Coon, O. Byungsung, Y. F. Lin, and M. H. Francombe, Appl. Phys. Lett. **53**, 1931 (1988).
[7] J. W. Choe, O. Byungsung, K. M. S. V. Bandara, and D. D. Coon, Superlattices Microstruct. **10**, 1 (1991).
[8] M. Zaluzny, Solid State Commun. **82**, 565 (1992).
[9] Y. Xu, G. Almogy, A. Shakouri, and A. Yariv, CLEO'95, Baltimore, paper CThQ4.
[10] G. Almogy, Y. Xu, A. Tong, A. Shakouri, and A. Yariv, Appl. Phys. Lett. **68**, 2088 (1996).
[11] Z. Ikonic, V. Milanovic, and D. Tjapkin, Solid State Commun. **72**, 835 (1989).
[12] E. B. Dupont, D. Delacourt, D. Papillon, J. P. Schnell, and M. Papuchon, Appl. Phys. Lett. **60**, 2121 (1992).